

## **A Unified Approach to Passive and Active Ocean Acoustic Waveguide Remote Sensing**

Principal Investigator: Nicholas C. Makris  
Massachusetts Institute of Technology  
77 Massachusetts Avenue, Room 5-222  
Cambridge, Massachusetts 02139  
phone: (617) 258-6104 fax: (617) 253-2350 email: [makris@mit.edu](mailto:makris@mit.edu)

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### **OBJECTIVES AND APPROACH**

Ocean acoustic waveguide remote sensing (OAWRS) is the basis for the primary undersea surveillance systems of the US Navy for both passive and active detection, localization, imaging and monitoring. Here OAWRS refers to all applications of acoustic remote sensing in an ocean waveguide. The primary objective of this work is to continue the data analysis and model development initiated in a series of major ocean acoustics experiments the PI has conducted which have recently been summarized in an invited paper in IEEE Spectrum [1].

We applied fundamental physical and statistical principles inherent in waveguide propagation and scattering to advance the state of the art in undersea surveillance. The approach was to use the extensive data analysis, software and fundamental waveguide scattering, propagation, reverberation and statistical models developed by the PI, his collaborators, graduate students and sub-contractors during the various experimental programs the PI has directed.

### **WORK COMPLETED/RESULTS**

Estimating velocity and force fields from image sequences is an essential and often first step of analysis in a wide variety of applications such as object detection and tracking, robot navigation, visual odometry, medical imaging, remote sensing and satellite imagery. Image sequences used in these applications describe both compressible and incompressible flows. We have developed methods for estimating forces which drive motion observed in density image sequences which have appeared as the spotlight paper in the June 2011 issue of the IEEE Transactions of Pattern Analysis and Machine Intelligence [6]. Using these forces, we also present methods for predicting velocity and density evolution. We formulate and apply a Minimum Energy Flow (MEF) method which is capable of estimating both incompressible and compressible flows from time-varying density images. Both the MEF and force estimation techniques are applied to experimentally obtained density images, spanning spatial scales from micrometers to several kilometers. Using density image sequences describing cell splitting, for example, we show that cell division is driven by gradients in apparent pressure within a cell. Using density image sequences of fish shoals, we also quantify (1) inter-shoal dynamics such as coalescence of fish groups over tens of kilometers, (2) fish mass flow between different parts of a large shoal and (3) the stresses acting on large fish shoals.

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Bistatic, long-range measurements of acoustic scattered returns from vertically extended, air-filled cylindrical targets were made during three distinct field experiments [12, 17, 19] in fluctuating continental shelf environments. It is shown that Sonar Equation estimates of mean target-scattered intensity lead to large errors, differing by an order of magnitude from both the measurements and waveguide scattering theory. This is because the sonar equation approximation is not applicable to targets large compared to the acoustic wavelength in an ocean waveguide. The use of the Ingenito scattering model is also shown to lead to significant errors in estimating mean target-scattered intensity in the field experiments because they were conducted in range-dependent ocean environments with large variations in sound speed structure over the depth of the targets, scenarios that violate basic assumptions of the Ingenito model. A Greens' theorem based full-field model that describes scattering from vertically extended cylindrical targets in range-dependent ocean waveguides by taking into account nonuniform sound speed structure over the target's depth extent is shown to accurately describe the statistics of the targets' scattered field in all three field experiments [5]. To account for the scintillation in the measured scattered intensity caused by fluctuations of the ocean waveguide, Monte-Carlo simulations of the scattered field are computed by implementing the full-field model in a range-dependent environment randomized by internal waves. Furthermore, the target-scattered returns are shown to have a very different spectral dependence than that of returns from target-like clutter such as fish schools that plague long-range navy sonars operating in continental shelves, so that multi-frequency measurements can be used to distinguish fish from man-made targets.

Doppler analysis has been extensively used in active radar and sonar sensing to estimate the speed and direction of a single target within an imaging system resolution cell following deterministic theory. For target swarms, such as fish and plankton in the ocean, and raindrops, birds and bats in the atmosphere, multiple randomly moving targets typically occupy a single resolution cell, making single-target theory inadequate. We develop for simultaneously estimating the instantaneous mean velocity and position of a group of randomly moving targets within a resolution cell, as well as the respective standard deviations across the group by Doppler analysis in free-space and in a stratified ocean waveguide [3]. While the variance of the field scattered from the swarm is shown to typically dominate over the mean in the range-velocity ambiguity function, cross-spectral coherence remains and maintains high Doppler velocity and position resolution even for coherent signal processing algorithms such as the matched filter. It is shown that for pseudo-random signals, the mean and variance of the swarms' velocity and position can be expressed in terms of the first two moments of the measured range-velocity ambiguity function. This is shown analytically for free-space and with Monte-Carlo simulations for an ocean waveguide.

The ability to accurately resolve remote surface orientation from measurements of fluctuating radiance is of great importance to ocean acoustics. All measurements made from sonar imaging systems are inherently corrupted by speckle noise. Due to the signal-dependent nature of speckle noise, and the often nonlinear relationship between surface orientation, illumination direction, and radiance, surface orientation estimates based on a single sample typically have large biases and mean-square errors (MSEs). A large number of samples may then be necessary to yield surface orientation estimates with tolerable biases and MSEs depending on the relative orientation of the surface with respect to the imaging system's source and receiver. A maximum likelihood method for estimating remote surface orientation from multi-static images corrupted by signal dependent noise is developed [2]. It is assumed that the noise arises from Gaussian field fluctuations and the surface properties are Lambertian. The biases and errors in surface orientation estimates for a single sample are shown to be highly sensitive to illumination direction, due to the signal-dependent nature of speckle noise and the nonlinear relationship between surface orientation, illumination direction and fluctuating radiance. The

minimum number of independent samples necessary for maximum likelihood estimates to be asymptotically unbiased and attain classical estimation theory's lower bound on resolution as well as practical design thresholds is derived.

We formulate a unified theory to model scattered returns from randomly distributed seafloor inhomogeneities in range-dependent ocean waveguides using the Rayleigh–Born approximation to Green's theorem using a full field matched filter approach [4]. The scattered field and total moment expressions are expressed as functions to fractional changes in density and compressibility of seafloor sediment. This model is implemented for a broadband source that uses matched-filter and beam forming to map the returns in range and bearing respectively. Calibration of modeled reverberation with data obtained during the OAWRS experiments enables estimation of seafloor parameters such as density, compressibility and coherence volume of inhomogeneities.

## **IMPACT/APPLICATIONS**

- We have published an invited paper in the IEEE Spectrum August 2011 issue, "IEEE's flagship publication" with over a ½ million subscribers, describing ONR basic research programs and advances in active Ocean Acoustic Waveguide Remote Sensing.
- We have developed a method to estimate forces which drive motion observed in density image sequences such as those generated during OAWRS experiments. It was the spotlight paper in the IEEE Transactions of Pattern Analysis and Machine Intelligence in June 2011.
- We have developed a model that describes scattering from vertically extended cylindrical targets in range-dependent ocean waveguides to help distinguish man-made targets from biological clutter.
- We have developed an analytical tool to estimate simultaneous clutter velocity and position using by Doppler analysis of acoustic remote sensing measurements.
- We have developed a method for estimating remote surface orientation of Lambertian surfaces from multi-static acoustic images that are corrupted by signal-dependent noise due to Gaussian field fluctuations.
- We have developed a full field matched filter approach to model reverberation in range-dependent waveguide environments.

## **TRANSITIONS**

Transition of the Acoustic Clutter Program is already significant as documented by the great amount of Naval Research now focusing on clutter issues in active sonar which was spearheaded and guided by the PI's various Acoustic Clutter programs. Recently, for example, this work helped start the Office of Naval Research (ONR) - Basic Research Challenge (BRC) program and several other Navy programs that focus on waveguide target scattering, clutter and attenuation.

## **RELATED PROJECTS**

Other organizations participating in the Geoclutter Program are Northeastern University, National Marine Fisheries Service, Institute of Marine Research Norway, NRL, ARL-PSU, MAI, UNH, RESON, SNWSC, and NFESC.

## RECENT RELEVANT PUBLICATIONS

1. N. C. Makris, "New Sonar Technology Reveals City-size Schools of Fish: Low-frequency sound waves improve ocean sensing," IEEE Spectrum (August, 2011).
2. Nicholas C. Makris and Ioannis Bertsatos, "Resolving Lambertian surface orientation from fluctuating radiance," J. Acoust. Soc. Am. 130, 1222-1231 (2011).
3. Ioannis Bertsatos and Nicholas C. Makris, "Estimating the Instantaneous Velocity of Randomly Moving Target Swarms in a Stratified Ocean Waveguide by Doppler Analysis," J. Acoust. Soc. Am. Volume 130(1), 84-101 (2011).
4. Anamaria Ignisca. *Analytic Model for Matched-filtered Scattered Intensity of volume inhomogeneities in an Ocean Waveguide Calibrated to Measured Seabed Reverberation*. Master of Science thesis, Massachusetts Institute of Technology, The Department of Mechanical Engineering, June 2011.
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